CP violation and CKM matrix elements at the B factories

J. Chauveau[a] *

[a] Laboratoire de Physique Nucléaire et de Hautes Energies,
IN2P3/CNRS, Université Pierre et Marie Curie-Paris6

Recent measurements at the B factories of CKM matrix elements affecting CP-violation are reviewed. The emphasis is on the unitarity triangle. Some aspects of the charm and τ sectors are mentioned.

1. INTRODUCTION

In the standard model (SM) the Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{ij} is the quark mixing coupling factor in the weak charged current connecting the i-th u-type quark to the j-th d-type quark and the W [1,2]. With three generations four real parameters are needed to describe the unitarity CKM matrix V, among which there is an irreducible phase which governs all CP violating phenomena. The unitarity relation built from the d and b columns of V defines a triangle in the complex plane. It is convenient to normalize the sides and to measure the phases with respect to $V_{cd}V_{cb}^*$, obtaining the unitarity triangle called the UT in the following. Its apex represents the complex number:

$$z = \overline{\rho} + i\overline{\eta} \equiv -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \tag{1}$$

whose imaginary part $\overline{\eta}$ governs CP violation. In other words, CP non-conservation means that the triangle is not squashed. Its angles α (ϕ_2) at the apex, γ (ϕ_3) at the origin and β (ϕ_1) differ from 0 or 180°. Use of the Wolfenstein parameterization [3] is customary with the definitions:

$$\lambda^2 \equiv \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \tag{2}$$

$$A^2\lambda^4 \equiv \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}. \tag{3}$$

λ is the sine of the Cabibbo angle and A is a real number of order unity. $\gamma = arg(z)$ is the opposite of the phase of V_{ub}.

*On behalf of the *BABAR* Collaboration

Many measurements contrain the apex of the UT. Dedicated teams produce global fits. I use the results of the CKMfitter group [4,5]. They are in fair agreement with those of the UTfit group [6], presented in another lecture [7] at this Conference.

The global fit pictured in Figure 1 and summarized in Table 1 shows the agreement of the experiments with the SM. While the Cabibbo angle is precisely measured, the accuracy on the other parameters ranges between 4 and 20%. In the following I review a subset of recent measurements of the angles and the sides of the UT.

Table 1
Global fit results from CKMfitter [4,5]. The uncertainties are quoted at the 68% confidence level.

A	$0.8184^{+0.0094}_{-0.0311}$
λ	$0.22512^{+0.00075}_{-0.00075}$
$\overline{\rho}$	$0.139^{+0.027}_{-0.023}$
$\overline{\eta}$	$0.342^{+0.016}_{-0.015}$

2. THE ANGLES

The angles β/ϕ_1 and α/ϕ_2 have been well measured since 2007. In contrast, progress is continously made in the determination of the angle γ/ϕ_3.

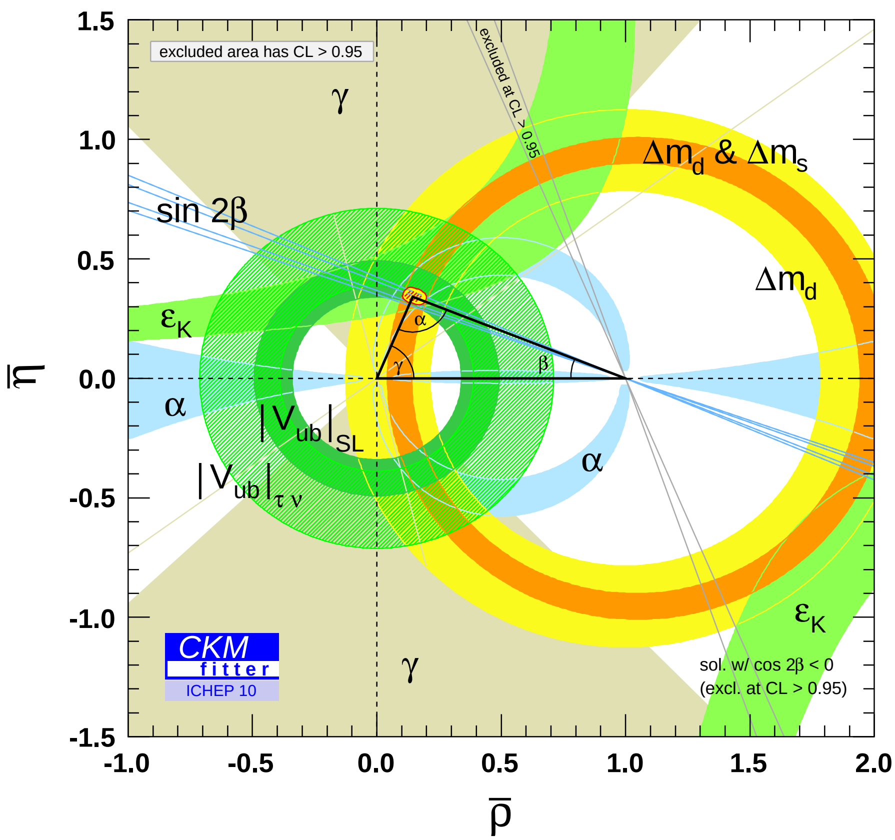

Figure 1. Figure from reference [4]. The constraints in the $(\overline{\rho},\overline{\eta})$ plane and the global CKM fit the 68% confidence level of which is shown as the hashed region. The $|V_{ub}|$ constraint is split into two contributions: that from B semileptonic decays (dark), and that from $B \to \tau\nu$ (hashed).

2.1. Recent results on the angle γ/ϕ_3

Three methods [8–10] are exploited to measure the angle γ/ϕ_3 in charged (or neutral) $B \to D^{(*)}K^{(*)}$ decays mediated by tree amplitudes. The relative phase of V_{ub} and V_{cb} appears in the interference of the diagrams of Figure 2, when they lead to the same final state $\underline{D}K$[2]. In the GLW method [8], the D^0 CP-eigenstates are selected. In the ADS method [9], the same final state is reached when the $b \to c$ transition is followed by a Doubly Cabibbo Suppressed D decay (DCSD) e.g. $D^0 \to K^+\pi^-$ or the $b \to u$ transition is followed by a Cabibbo allowed D decay (CA) e.g. $\overline{D}^0 \to K^+\pi^-$. In the GGSZ method [10] the rich structure (Dalitz plot) of a flavor-blind 3-body D decay is the key. Large uncertainties affect the measurements because the rates are low or the two decay paths have disparate magnitudes. As the CA and DCSD D decay rates are precisely known, the measured in-

[2] We generically use $\underline{D}$ for $D/\overline{D}$ as both feed the final state.

terference patterns are governed by r_B the ratio of the $b \to u$ and $b \to c$ magnitudes, δ_B and δ_D the strong phase shifts in the B and D decays of the 2 paths, and γ/ϕ_3. Recent results have been obtained using ADS and GGSZ by the *BABAR* and Belle collaborations, which we now summarize.

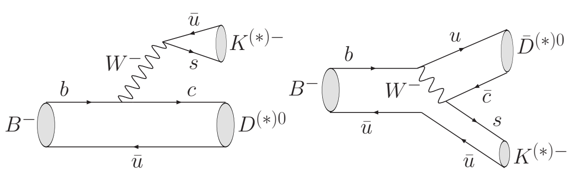

Figure 2. ADS method. Feynman diagrams of the $b \to u$ and $b \to c$ processes which interfere in the decay $B^- \to \underline{D}K^-$.

The observables in the ADS method are the CP-averaged $b \to u$ / $b \to c$ ratio of decay rates R_{ADS}, and the CP asymmetry A_{ADS}. The sensitivity to the angle γ/ϕ_3 is apparent from the relations:

$$R_{ADS} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\gamma \quad (4)$$

$$A_{ADS} = [2r_B r_D \sin(\delta_B + \delta_D)\sin\gamma]/R_{ADS}. \quad (5)$$

BABAR [11] has recently measured these quantities in the three channels $B^- \to K^- + \underline{D^0}, D^{*0}[\to (\pi^0 \text{ or } \gamma) + \underline{D^0}]$ (Table 2) and observed indications of signals at the two standard deviation significance level in the first two. The GGSZ method [10] has been used to interpret the measurements of the same B decays and $B \to D^0 K^*(892)$ where the D^0 meson decays into 3-body channels $\underline{D^0} \to K_S^0\pi^+\pi^-$ [12] and $\underline{D^0} \to K_S^0\pi^+\pi^-$, $K_S^0 K^+ K^-$ [13] using respectively 657 and 468 millions $B\overline{B}$ pairs. The resulting *cartesian coordinates*

$$x^{\pm} \equiv r_B\cos(\delta_B \pm \gamma);\ y^{\pm} \equiv r_B\sin(\delta_B \pm \gamma) \quad (6)$$

provide the best determination to date of the angle γ/ϕ_3. The *BABAR* measurements are shown on Figure 3. Table 3 lists the measurements of γ/ϕ_3 and the ancillary parameters from *BABAR* and Belle. The results of the two experiments are compatible, both claim evidence for direct CP violation ($\gamma \neq 0$) at the 3.5 standard deviation level. The combination by the CKMfitter group of all measurements gives $\gamma_{comb} = 70^{+14}_{-21}{}^\circ$ to be compared to the global CKM fit (leaving the γ measurements aside) result $\gamma_{CKMfit} = 67.4 \pm 3.9^\circ$.

2.2. The β/ϕ_1 and α/ϕ_2 angles

Using all measurements of $B \to$ charmonium + $K_{S,L}$ the heavy flavor averaging group (HFAG) determines [14] $\sin 2\beta = 0.673 \pm 0.023$ which translates into either $\beta/\phi_1 = 21.1 \pm 0.9^\circ$ or $69.9 \pm 0.9^\circ$. The former value is slightly preferred experimentally and matches the other contraints in the global CKM fit wich validates the SM. It has to be noted that the most recent measurements done using Dalitz-plot amplitude analyses (e.g for $B \to \pi^+\pi^- K_S^0$ [15,16]) determine the angle β/ϕ_1 without trigonometric ambiguity. However they are less precise.

The α/ϕ_2 angle is precisely determined by the $B \to \pi\pi$, $\rho\pi$ and $\rho\rho$ decays, analyzed using isospin relations to disentangle tree and penguin decay paths. Combining all experimental results the CKMfitter group finds $\alpha_{comb} = 89^{+4.4}_{-4.2}{}^\circ$ which compares well to the global fit (leaving the α measurements aside) result, $\alpha_{CKMfit} = 97.5^{+1.6}_{-8.1}{}^\circ$.

In summary the measurements of the angles β/ϕ_1 and α/ϕ_2 alone constrain the apex of the UT enough to establish that CP is violated in B decays. The determination of the γ/ϕ_3 angle is not yet accurate enough to further constrain the KM model. The GLW, ADS and GGSZ methods are effective at LHCb. With them very clean measurements of the γ/ϕ_3 angle in pure tree processes will be obtained which will establish a solid basis for new physics searches in γ-sensitive decays proceeding via loop diagrams.

3. THE SIDES

I refer to the recent review of the determination of $|V_{ub}|$ and $|V_{cb}|$ from the semileptonic B meson decays at the B-factories [17] and the compilation of the Review of Particle Properties [18].

Table 2
ADS results from BABAR [11].

channel	$R_{ADS} \times 10^2$	significance	A_{ADS}
DK	$1.1 \pm 0.5 \pm 0.2$	2.1σ	$-0.86 \pm 0.47^{+0.12}_{-0.16}$
$D^{*0}K, D^{*0} \to D^0\pi^0$	$1.9 \pm 0.9 \pm 0.4$	2.2σ	$+0.77 \pm 0.35 \pm 0.12$
$D^{*0}K, D^{*0} \to D^0\gamma$	$1.3 \pm 1.4 \pm 0.8$	–	$+0.36 \pm 0.94^{+0.25}_{-0.41}$

Table 3
GGSZ results from BABAR [13] and Belle [12].

Parameter	Experiment	68% CL (stat.)	exp. systematics	Dalitz model syst.
$\gamma/\phi_3(^\circ)$	BABAR	68^{+15}_{-14}	± 4	± 3
	Belle	$78.4^{+10.8}_{-11.6}$	± 3.6	± 8.9
$r_B(DK)$	BABAR	0.096 ± 2.9	± 0.005	± 0.004
	Belle	$0.160^{+0.040}_{-0.038}$	± 0.011	$^{+0.050}_{-0.010}$
$r_B(D^*K)$	BABAR	$0.133^{+0.042}_{-0.039}$	± 0.013	± 0.003
	Belle	$0.196^{+0.072}_{-0.069}$	± 0.012	$^{+0.062}_{-0.012}$
$r_B^{eff}(DK^*)$	BABAR	$0.149^{+0.066}_{-0.062}$	± 0.026	± 0.006
$\delta_B(DK)(^\circ)$	BABAR	119^{+19}_{-20}	± 3	± 3
	Belle	$136.7^{+13.0}_{-15.8}$	± 4	± 22.9
$\delta_B(D^*K)(^\circ)$	BABAR	-82 ± 21	± 5	± 3
	Belle	$-18.1^{+18.0}_{-18.6}$	± 3	± 22.9
$\delta_B^{eff}(DK^*)(^\circ)$	BABAR	111 ± 32	± 11	± 3

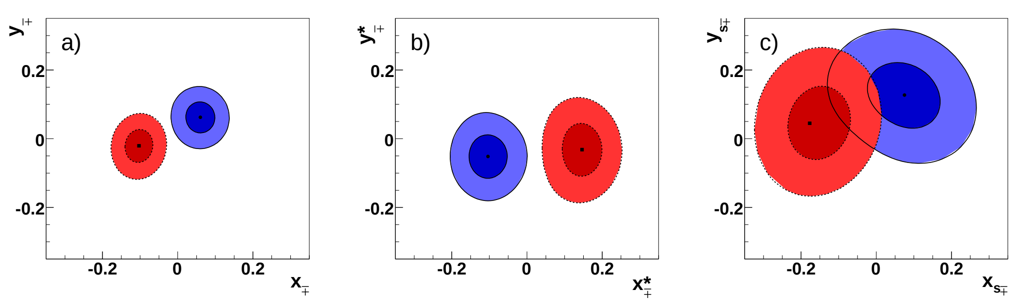

Figure 3. Figure from reference [13]. Contours at 39.3% (dark) and 86.5% (light) 2-dimensional confidence levels in the cartesian coordinate planes for (a) DK, (b) D^*K, and (c) DK^*, corresponding to one- and two-standard deviation regions (statistical only), for B^- (solid lines) and B^+ (dotted lines) decays. The two contours in each picture would coincide if CP were conserved. The angle between the (to-be-imagined) straight lines joining the $(x = 0, y = 0)$ point to the two contour centers is equal to 2γ.

With increased statistics, well established analysis techniques still progress. Tagged samples of $B\overline{B}$ events where the *other* B meson is reconstructed now contribute. Event selection algorithms have been devised that increase the acceptance of $b \to u\ell\nu$ decays over wide kinematical ranges. Inclusive and exclusive semileptonic decays are both relevant. The former are modeled theoretically using Operator Product Expansions (OPE) by expressions in terms of α_s and $\frac{\Lambda_{QCD}}{m_b}$

with useful commonalities with those describing the $B \to X_s\gamma$ inclusive radiative decays. The exclusive semilptonic decays rely on sets of form factors conform to Heavy Quark Symmetry and lattice QCD (LQCD) computations. $|V_{ub}|$ is also constrained by the purely leptonic $B \to \tau\nu$ decay, simpler to model but with a dependence on the B meson decay constant to be computed from LQCD.

3.1. V_{cb}

The current exclusive $B \to D^*\ell\nu$ measurements combined with a recent unquenched lattice calculation [19] lead to $|V_{cb}| = (38.7 \pm 0.9 \pm 1.0) \times 10^{-3}$, where the experimental uncertainty is quoted first followed by that of the LQCD calculations. A new tagged analysis from BABAR [20] of $B \to D\ell\nu$ has a significantly improved accuracy. With an unquenched lattice form factor calculation [21], it leads to $|V_{cb}| = (39.1 \pm 1.4 \pm 1.3) \times 10^{-3}$. Global fits to the inclusive decay rates and $\simeq 60$ moments of the lepton energy and hadronic mass spectra [22] as well the $B \to X_s\gamma$ photon energy spectrum [23] are performed to extract $|V_{cb}|$, hadronic coefficients and the b quark mass within a given renormalization scheme. The average [17,14] for inclusive decays is $|V_{cb}| = (41.9 \pm 0.4 \pm 0.6) \times 10^{-3}$. The agreement between the $|V_{ub}|$ determinations from exclusive and inclusive decays is marginal. The uncertainties have to be scaled up in order to quote the average $< |V_{cb}| >= (40.9 \pm 1.0) \times 10^{-3}$.

3.2. V_{ub}

Because the rates are suppressed, the background from $b \to c$ processes is high and the inclusive measurements are harder. Strict selections are implemented which reduce the accepted phase space. Therefore the applicability of OPE is impaired unless one uses a *shape function* [17,18]. Weak annihilations contribute. Furthermore, a recent calculation [24] shows that QCD effects at the NNLO are sizeable. With high statistics however, innovative analysis techniques are implemented. For instance, with multivariate techniques Belle [25] accesses 90% of the available phase space. Inclusive determinations average [17] to: $|V_{ub}| = (4.37 \pm 0.16 \pm 0.20 \pm 0.30) \times 10^{-3}$, where the first uncertainty is experimental, the second is from the spread of theoretical results and the third is the NNLO effect.

A preliminary result from BABAR [26] on $B \to \pi\ell\nu$ comes out of a fit of the differential branching fraction as a function of q^2 which uses data points from the experiment as well as from a lattice calculation [27]. The result, $|V_{ub}| = (2.95 \pm 0.31) \times 10^{-3}$ where the uncertainty combines the experimental and theoretical contributions, is lower by $\simeq 20\%$ from previous averages. There again and more significantly than for $|V_{cb}|$, the exclusive and inclusive averages are far apart. Recent findings tend to increase the discrepancy. This should be kept in mind when considering that the global CKM fits inputs are the averages of the exclusive and inclusive determinations of $|V_{ub}|$ and $|V_{cb}|$.

A stronger feature involving $|V_{ub}|$ comes from the determination of the $B \to \tau\nu$ branching fraction. A higher value than that from the semileptonic decays is preferred by the data from BABAR and Belle and this bring a much discussed tension in the global CKM fits with the constraint from $\sin 2\beta$. I refer to the thorough description of that issue [28] at this workshop.

3.3. V_{ts}/V_{td}

The $\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}$ side of the UT remains to be discussed. The most accurate relevant contraints come from measurements [4] of $|\frac{V_{ts}}{V_{td}}|$, currently dominated by B_s mixing [29]. A new BABAR measurement [30] of the inclusive decays to $B \to X_{s,d}\gamma$ brings a contribution with independent systematic uncertainties: $|\frac{V_{ts}}{V_{td}}| = 0.199 \pm 0.022 \pm 0.024 \pm 0.002$, where the last uncertainty after the statistical and the systematic components is from theory.

4. OTHER TOPICS

For lack of time in Capri and lack of place here, I do not describe two topics. Recent attempts to check the unitarity of the first row of the CKM matrix using strange and non-strange τ decays are conclusive with exclusive ($\pi\nu$ and Kν) decays; but not yet with inclusive ones. To date, there no evidence of CP violation in D meson mixing.

5. SUMMARY AND OUTLOOK

CP violation in B meson decays has been established. The KM model works to explain CP violation phenomena observed with quarks. The global CKM fits reveal some tensions. The contrary would be suspicious... None are overwhelming. Each should be scrutinized. There is room for New Physics which could appear as corrections of order 10% to flavor parameters. Many measurements are statistically limited. Now is the time of the hadron machines (TeVatron, LHCb). Hopefully New Physics will unveil. However e^+e^- colliders are invaluable to pursue a comprehensive experimental program. Still the antimatter problem remains unexplained.

6. ACKNOWLEDGEMENTS

I am very grateful to have been invited at the Capri workshop. Many thanks to the organisers, the *BaBar* Collaboration and to LPNHE and IN2P3/CNRS. Special thanks to the CKMfitter group for sharing their most recent results.

REFERENCES

1. N. Cabibbo, Phys. Rev. Lett **10**, 531 (1963).
2. M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
3. L. Wolfenstein, Phys. Rev. Lett. **51**, 1945 (1983).
4. CKMfitter Group (J. Charles et al.), Eur. Phys. J. **C41**, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: http://ckmfitter.in2p3.fr
5. S. Descôtes-Genon, Invited talk at the VIIIth Workshop on Flavor Physics & CP Violation (FPCP 2010), May 25-29,, Torino, Italy; to appear in proceedings.
6. M. Ciuchini et al., JHEP **0107**, 013 (2001).
7. M. Ciuchini, these proceedings.
8. M. Gronau and D. London, Phys. Lett. **B253**, 483 (1991); M. Gronau and D. Wyler, Phys. Lett. **B265**, 172 (1991).
9. D. Atwood, I. Dunietz, and A. Soni, Phys. Rev. Lett., **78**, 3257 (1997); Phys. Rev. D **63**, 036005 (2001).
10. A. Giri, Y. Grossman, A. Soffer, and J. Zupan, Phys. Rev. D **68**, 054018 (2003).
11. *BaBar* Collaboration, P. del Amo Sanchez et al., arXiv:1006.4241v1 [hep-ex], accepted by Phys. Rev. D.
12. Belle Collaboration, A. Poluetkov et al., Phys. Rev. D **81**, 112002 (2010).
13. *BaBar* Collaboration, P. del Amo Sanchez et al., Phys. Rev. Lett **105**, 121801 (2010).
14. `http://www.slac.stanford.edu/xorg/hfag`.
15. *BaBar* Collaboration, B. Aubert et al., Phys. Rev. D **80**, 112001 (2009).
16. Belle Collaboration, J. Dalseno et al., Phys. Rev. D **79**, 072004, (2009).
17. R. Kowalewski, Invited talk at the VIIIth Workshop on Flavor Physics & CP Violation (FPCP 2010), May 25-29,, Torino, Italy; to appear in proceedings.
18. R. Kowalewski and T. Mannel in K. Nakamura et al. (Particle Data Group), J. Phys. G **37**, 075021 (2010).
19. FNAL Lattice & MILC Collaborations, D. Bernard et al., Phys. Rev. **D 79**, 014506 (2009).
20. *BaBar* Collaboration, B. Aubert et al., Phys. Rev. Lett. **104**, 011802 (2010).
21. M. Okamoto, Plenary talk at Lattice 2005, Dublin, July 25-30, 2005, PoS LAT2005, 013 (2005).
22. *BaBar* Collaboration, B. Aubert et al., Phys. Rev. D **81**, 032003 (2010).
23. Belle Collaboration, A. Limosani et al., Phys. Rev. Lett. **103**, 241801 (2009).
24. B.O. Lange et al., Phys. Rev. D **72**, 073006 (2005).
25. Belle Collaboration, P. Urquijo et al., Phys. Rev. Lett. **104**, 021801 (2010).
26. *BaBar* Collaboration, P. del Amo Sanchez et al., arXiv:1005.3288v1 [hep-ex], submitted to Phys. Rev. D.
27. FNAL Lattice & MILC Collaborations, J.A. Bailey et al., Phys. Rev. D **79**, 054507 (2009).
28. C. Schwanda, these proceedings.
29. CDF Collaboration, A. Abulencia et al., Phys. Rev. Lett. **97**, 242003 (2006).
30. *BaBar* Collaboration, P. del Amo Sanchez et al., Phys. Rev. D **82**, 051101(R) (2010).